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EFFECT OF ANTENNA OPERATION ON STRUCTURE AND FOUNDATION BEHAVIOR FPS-26 TOWERS, BELLEFONTAINE AIR FORCE STATION, OHIO AND KEESLER AIR FORCE BASE, MISSISSIPPI

R. F. Ballard, Jr., et al

Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

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Details of illustrations in
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studied on microfiche.

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FOREWORD

The investigations reported herein comprise a portion of the study of foundation behavior under dynamic loadings which is being performed for the Office, Chief of Engineers, by the U. S. Army Engineer Waterways Experiment Station (WES) in accordance with "Instructions and Outline, Development and Evaluation of Soil Bearing Capacity, FY 1962-63." This report describes dynamic loading tests of the FPS-26 radar towers at Bellefontaine Air Force Station, Ohio, and Keesler Air Force Base, Miss., on 18 and 19 April and 14 through 17 May 1963, respectively, performed in conjunction with U. S. Army Engineer Ohio River Division Laboratories.

Engineers of the Soils Division, WES, actively engaged in the data collection, analysis, and report phases of this study were Messrs. R. W. Cunny, Z. B. Fry, R. F. Ballard, Jr., Jack Fowler, and R. A. Weiss. The work was under the general supervision of Messrs. W. J. Turnbull, Chief, Soils Division, W. G. Shockley, formerly Assistant Chief, Soils Division, and A. A. Maxwell, Assistant Chief, Soils Division. This report was prepared by Messrs. Ballard and Fowler.

Director of the WES during this investigation and the preparation of this report was Col. Alex G. Sutton, Jr., CE. Technical Director was Mr. J. B. Tiffany.

CONTENTS

SUMMARY

The investigation reported herein describes the techniques used to instrument FPS-26 type radar towers at Bellefontaine Air Force Station (BAFS), Ohio, and Keesler Air Force Base (KAFB), Miss., and the study conducted to determine the effects of operation of the structures' antenna in regard to movement of the structure and its mat foundation. Specifically, these tests were conducted to determine the displacements, frequencies, and direction and phase of movement of the FPS-26 tower structure and foundation. The two tower structures (one each at BAFS and KAFB) were identical, except that the BAFS tower was constructed 25 ft higher than the KAFB tower by extending the foundation supports to the first floor by this amount.

Transducers were positioned to measure movement in three planes: horizontal, tangent to the path of rotation of the antenna (X-axis); horizontal, perpendicular to the path of rotation of the antenna (Y-axis); and vertical (Z-axis).

It was determined from the BAFS and KAFB towers that the largest displacements occurred along the X-axis at the antenna pedestal level in the twisting, or torsional, mode when the antenna stopped after a slewing operation. The average maximum displacement along the X-axis at the antenna pedestal level for the BAFS tower was 114.2×10^{-4} in. Similar test conditions at the KAFB tower produced an average maximum displacement of 126.5×10^{-4} in., as determined by a conventional velocity-type transducer. Precision displacement potentiometers were also used along the X-axis plane during the tests at KAFB. These instruments substantiated (within 10 percent instrumentation tolerances) movements recorded by the velocity-type transducers. Average

maximum movement recorded at the foundation footing at the BAFS tower was 6.2×10^{-4} in. Comparable tests at KAFB indicated movements of 3.2×10^{-4} in.

Frequencies recorded at BAFS were predominantly 7 cps along the X-axis and 20 cps along the Y- and Z-axes while the antenna was slewing. At KAFB, frequencies obtained along X-, Y-, and Z-axes with the antenna slewing were 7, 22, and 12 cps, respectively, as determined from oscillograph recordings and a frequency spectrum analyzer. Nodding (rocking) the antenna with and without azimuth rotation did not contribute a significant amount of movement to the tower. Acceleration (1.14 radians per sec^2), rise time (1.18 sec), maximum velocity (1.35 radians per sec), and deceleration (2.52 radians per sec^2) for both towers were virtually the same for comparable azimuth rotations. Phase relations were recognizable between transducers in different locations, thus depicting a time-scale response of the structure when subjected to impulse loadings by operation of the antenna. As might be expected, the phase response of the structure was much greater along the X-axis (torsional mode) than along the Y- and Z-axes. A theoretical analysis was made to determine the realistic significance of the data acquired at each test site. Two approaches, the Reissner-Sung theory and a weighted spring, mass, and dashpot analytical method, were used. This analysis, which is beyond the scope of presentation in this report, confirmed the relation of torsional movements and the recorded frequency range of 18 to 22 cps. The rocking mode was related to the 7-cps frequency, and sliding movements were associated with the recorded frequency of 12 cps.

EFFECT OF ANTENNA OPERATION ON STRUCTURE AND FOUNDATION BEHAVIOR, FPS-26 TOWERS, BELLEFONTAINE AIR FORCE STATION, OHIO, AND KEESLER AIR FORCE BASE, MISSISSIPPI

PART I: BACKGROUND, PURPOSE, AND SCOPE OF STUDY

1. The investigation reported herein is part of an overall study concerned primarily with problems arising in foundation design for radar facilities with extremely high stability requirements under dynamic loadings. Investigations performed in connection with the overall study have consisted of dynamic loadings applied in three modes of vibration (vertical, torsional, and rocking) to small-scale foundations,* and measurements made on a Nike-Zeus target-tracking radar structure at the White Sands Missile Range, New Mexico, to determine the vibration and movement of a prototype structure during its operation.** After these investigations were completed, consultants for the study recommended that additional prototype structures be instrumented to compare and/or correlate the data obtained with results of the model studies. Accordingly, arrangements were made for the U. S. Army Engineer Waterways Experiment Station (WES) to participate in a series of tests which was being performed by the Ohio River Division Laboratories (ORDL) on FPS-26 radar facilities at Bellefontaine Air Force Station (BAFS), Ohio, and Keesler Air Force Base (KAFB), Miss.

2. This report describes the studies performed by WES in these tests, the specific purpose of which was to determine the effect of forces imposed by operation of the antenna on amplitude, frequency, direction, and phase of movement of the FPS-26 structures and foundations.

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* U. S. Army Engineer Waterways Experiment Station, CE, Development and Evaluation of Soil Bearing Capacity, Foundations of Structures; Field Vibratory Tests Data, Technical Report No. 3-632, Report 1 (Vicksburg, Miss., July 1963).

** U. S. Army Engineer Waterways Experiment Station, CE, Effect of Antenna Operation on Structure and Foundation Behavior, TTR Tower, White Sands Missile Range, New Mexico, Miscellaneous Paper No. 4-580 (Vicksburg, Miss., June 1963).

PART II: THE INVESTIGATION

Location and Topography of Test Sites

BAFS

3. The FPS-26 radar tower at BAFS is located within the installation, approximately 3 miles east of Bellefontaine, Ohio. The terrain in this area is gently rolling to hilly. The tower is situated on a hillside slope on which a fill of shaley clay material was constructed to establish the necessary grade for the structure. The original and existing ground-surface elevations are shown in plate 1. Exploratory borings at BAFS indicated that the natural subsoils consist of stiff to very stiff clayey silt materials to approximately 20 ft and silt to silty clay to a depth of 40 ft below the tower mat. Traces of sand and gravel were found throughout the explored depth. Groundwater was encountered 16 ft below the base of the tower mat.*

KAFB

4. The FPS-26 radar tower at KAFB is located near the base, approximately 5 miles west of Biloxi, Mississippi. The terrain in this area is flat and sandy. The tower foundation was located on a uniform, fine sand material (SP) that is predominant in this area. No soil boring logs were available at the time of this report's inception.

Description and Inspection of Structures

5. The FPS-26 structural-steel radar towers at BAFS and KAFB were constructed within, but independent (i.e. independent above the foundation level) of an outer, steel-frame building (plates 1 and 2). The tower structure (triangular in shape) consists of three 6-3/4-in. solid-steel columns with steel stiffeners and concrete slabs at the floor and roof levels (see plates 3 and 4). The only major difference in the construction of the towers is the overall height of the two structures. The BAFS tower

* U. S. Army Engineer Ohio River Division Laboratories, CE, Data Report on the Results of Tests on FPS-26 Radar Tower, Bellefontaine Air Force Station, Bellefontaine, Ohio (Cincinnati, Ohio, May 1963).

was constructed 25 ft higher than the KAFB tower by merely extending the foundation supports to the first floor by this amount. The tops of the antenna platforms for the BAFS and KAFB towers are 53 and 28 ft above ground surface, respectively. Each tower structure and its interior 8-WF steel columns are supported by a 24-in.-thick, 18-ft-3-in. by 18-ft-9-in. reinforced-concrete mat 6 ft below the ground surface. The structural-steel members of the towers are bolt-connected, except for the connecting plates attached to the solid, round columns.

6. The antenna structure for both the BAFS and the KAFB towers weighs approximately 5400 lb, slews in an azimuth direction only, and is capable of nodding in a vertical direction from -2 to +32 deg from the horizontal at a maximum nodding frequency of 19 cycles per minute (cpm). The antenna structure in nodding has eccentric loadings of 250 ft-lb at an eccentricity of 1 ft. The maximum slew speed in a 180-deg travel path, stop to stop, is 3.4 sec.

7. A preliminary inspection of the FPS-26 towers was made to determine the accessible areas for placement of transducers. From observations of the movements of the towers with the antenna slewing, it was found that velocity- or accelerometer-type pickups could be attached to the three 6-3/4-in.-diameter, solid-steel tower columns and the concrete foundations.

Test Program

8. The initial concept was to place transducers at various heights on any one of the tower's support columns and on its foundation footing. The transducers were to be oriented in three planes, X, Y, and Z, to determine the torsional, rocking, and vertical movements. Therefore, a set, or group, of three transducers was to be placed at each selected location and positioned to measure movement tangent (X-axis, fig. 1), perpendicular (Y-axis, fig. 1), and vertical (Z-axis) to the path of rotation of the antenna. The antenna was to be operated in slewing

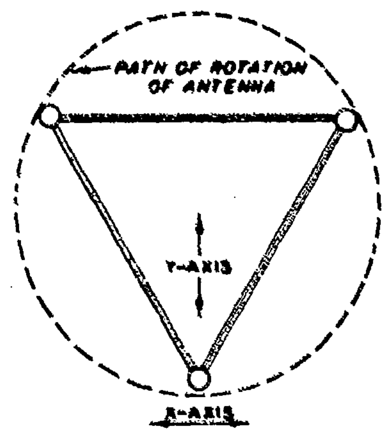

Fig. 1. Orientation of planes along which transducers were positioned to measure horizontal movement

(torsional) and nodding (rocking) movements and in a combination of both. Three separate series of tests were planned as follows:

Test Series No.	Antenna Operation
1	Slewing through 90- and 180-deg rotations without nodding
2	Slewing through 90- and 180-deg rotation nodding at maximum rate
3	Nodding only (no slewing movement) at 0-, 45-, 90-, and 180-deg azimuth position (referenced to the instrumented column, which was designated as 0 deg)

The actual tests performed on the BAFS and KAFB towers followed the proposed plan of tests.

Types and Positioning of Equipment

9. The transducers consisted of 2g and 3g accelerometers and velocity-type pickups. Mountings for the transducers were affixed to the tower structure and foundation with epoxy glue at predetermined locations (see figs. 2 and 3). The BAFS tower structure was instrumented with two velocity pickups and an accelerometer for measurement of displacement along the X-, Y-, and Z-axes and frequencies at each of four levels (see plate 3): location 1, antenna pedestal; location 2, first-floor level, 25 ft above ground surface; location 3, tower structure near column footing; and location 4, column footing at ground level. The KAFB tower structure was instrumented with the same grouping of transducers at each of four levels (see plate 4): location 1, antenna pedestal; location 2, second-floor level, 15 ft above ground surface; location 3, first-floor level, 2 ft above ground surface; and location 4, column footing at ground level. During certain of the tests, the set of transducers at location 2 was removed from the tower structure and used at location 4 on the column footing as there were only three sets of transducers available.

10. The transducer outputs were amplified and recorded on tape and oscillograph paper. The antenna motion was correlated with the oscillograph record by means of a timing system which electronically supplied

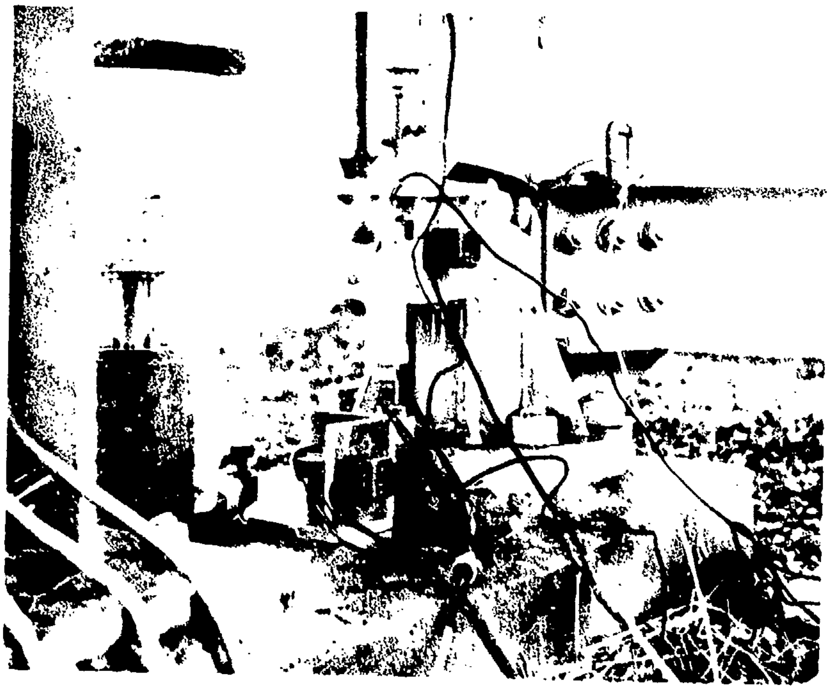

Fig. 2. X-, Y-, and Z-axis transducers positioned on column (location 3) and footing (location 4) at BAFS

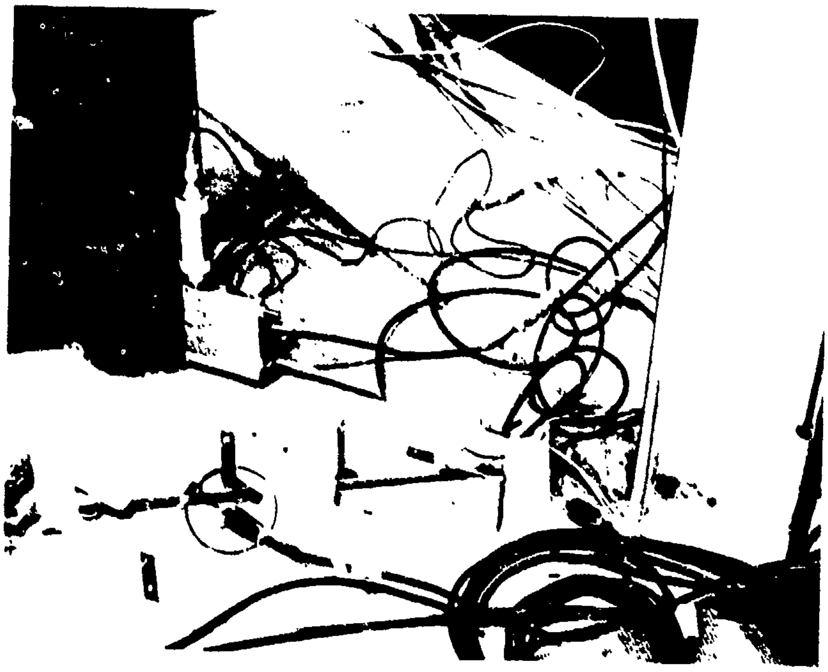

Fig. 3. X-, Y-, and Z-axis transducers positioned on column (location 3) at KAFB. In the center foreground are ORDL displacement gages. A WES precision potentiometer is at the left

a timing mark to the recorder for synchronization. The timing system also supplied a timing mark to another recorder used to monitor the antenna tachometer which generated a direct-current voltage directly related to antenna velocity. A tachometer record was obtained for each individual test run. By comparing the oscillograph and tachometer records, it was possible to determine the exact time the antenna started; the acceleration, maximum velocity, and deceleration of the antenna; and the time the antenna motion ceased. In addition to the instrumentation used in the BAFS tests, two potentiometers were installed on the KAFB tower to determine displacement along the X-axis at the antenna-pedestal and first-floor levels. These displacement gages were referenced to the building structure, which was completely isolated from the antenna support columns.

PART III: TEST RESULTS AND ANALYSIS

Tachometer Data

11. As stated in paragraph 10, tachometer recordings were taken for each test conducted at both BAFS and KAFB. These recordings for both towers were virtually identical for every comparable test. Representative recordings for both towers are shown in plate 5. Regardless of starting and stopping positions, the antennae exhibited approximately the same results for comparable azimuth slews. For clarity, it is considered that the starting period is the time required for the antenna to accelerate from a stationary position to its programmed velocity rate; the operation period is then considered to be the time of constant velocity; and the stopping period is the time required by the antenna to decelerate from operational velocity to a complete stop. The durations of the starting, operating, and stopping periods are shown below, together with acceleration, deceleration, and velocity values that represent the 0- to 90- and 0- to 180-deg slews.

Event	Duration sec	Acceleration radians/sec^2	Velocity radians/sec
		0 to 90 deg	
Starting	1.18	+1.14	--
Operating	0.46	--	1.35
Stopping	0.54	-2.52*	--
Total time	2.18		
		0 to 180 deg	
Starting	1.18	+1.14	--
Operating	1.68	--	1.35
Stopping	0.54	-2.52	--
Total time	3.40		

* The minus sign indicates deceleration.

Repeated tests showed the tachometer recording data to be almost identical for both towers. For the 45-deg slew, the antenna on the KAFB tower accelerated and decelerated in the same manner as for the 90- and 180-deg slews, but did not reach maximum velocity.

Test Series 1

BAFS

12. The tests conducted in this series were performed with the antenna slewing in the azimuth plane only (clockwise rotation) without any nodding component. Transducers were located on the north column (plate 3) and its foundation footing, which was arbitrarily designated as the 0-deg reference point. Velocity-type pickups were used to monitor the movements along the X- and Z-axes, and accelerometers were used for movements along the Y-axis. Two 90-deg (0 to 90 deg and 180 to 270 deg) and two 180-deg (0 to 180 deg and 180 to 360 deg) azimuth slews were made with the transducers positioned at locations 1, 2, and 3. The same antenna movements were conducted again with pickups placed in locations 1, 3, and 4.

13. Table 1 shows the maximum displacements and the frequencies that occurred at each location during the starting and stopping of the antenna. Displacements for the 90- and 180-deg slews were approximately the same. In order to utilize the data recorded on tape to the greatest advantage, it was decided to filter the data through a 35-cps high-cut instrument to verify the predominant frequencies of 20 and 7 cps shown in table 1 and the wave shapes interpreted from the original unfiltered oscillograph recording used for actual data reduction. The filtered data, which removed the 100- to 500-cps high-frequency noise originating from the servomotors and other mechanical devices, validated the frequencies selected from the raw field data. In addition to the filter method, a frequency spectrum analysis was performed utilizing a General Radio Vibration Analyzer (type 762). This analysis confirmed predominant frequencies.

14. Average maximum displacements and frequencies recorded at location 1 during periods of antenna starting and stopping were as follows:

	Start		Stop	
Orientation	Displacement in. x 10^{-4}	Frequency cps	Displacement in. x 10^{-4}	Frequency cps
Vertical (Z-axis)	28.3	20	45.9	20
Horizontal (X-axis)	74.3	--	11[illegible].6	7
Horizontal (Y-axis)	56.7	20	106.3	20

Foundation response at location 4 resulted in the following average maximum displacements and frequencies:

	Start		Stop	
Orientation	Displacement in. x 10^{-4}	Frequency cps	Displacement in. x 10^{-4}	Frequency cps
Vertical (Z-axis)	0.8	20	1.4	20
Horizontal (X-axis)	2.4	--	6.2	7
Horizontal (Y-axis)	0.6	20	2.2	20

15. It is readily seen from these data that the greatest amplitudes occurred along the X-axis. No starting frequency was used for reduction of the X-axis data because the sharp wave form produced by the initial antenna movement very nearly approached the shape of a sharp symmetrical sawtooth function rather than the conventional sinusoid. Therefore, the displacement in this case was obtained by integrating the area under this curve with respect to its time duration, which was approximately 20 msec. Data reduction for the stopping movements was performed in the normal manner of sinusoidal integration, since accurate frequency determinations could be made from the oscillograph recording.

<u>KAFB</u>

16. Tests were conducted at the KAFB site in the same manner as at BAFS. A single support column, the north column, and its foundation footing were instrumented (plate 4). This column was arbitrarily designated as the 0-deg reference point. Two 180-deg (0 to 180 deg and 180 to 360 deg) azimuth slews were made with the pickups positioned at locations 1, 2, and 3. The transducers were then repositioned at locations 1, 2, and 4. Recordings were then made with the antenna performing azimuth slews through 45 deg (0 to 45 deg), 90 deg (0 to 90 deg and 180 to 270 deg), and 180 deg (0 to 180 deg and 180 to 360 deg). These data are given in table 2.

17. Displacement data in table 2 indicate that the largest amplitudes occurred at location 1 and that stopping amplitudes exceeded starting movements by a factor of about 2. It should also be noted that displacements incurred by the support pedestal indicate that neither the starting position nor the total number of degrees traveled by the antenna made any significant change in maximum structure movements. The average

maximum values at location 1 are tabulated as follows:

Orientation	Transducer	Start: Displacement in. × 10^{-4}	Start: Frequency cps	Stop: Displacement in. × 10^{-4}	Stop: Frequency cps
Vertical (Z-axis)	Velocity pickup	16.6	12	38.8	12
Horizontal (X-axis)	Velocity pickup	53.3	7	112.2	7
Horizontal (X-axis)	Potentiometer	67.1	7	137.4	7
Horizontal (Y-axis)	Accelerometer	15.3	22	16.6	22

Average maximum values recorded at the foundation level (location 4) were as follows:

Orientation	Transducer	Start: Displacement in. × 10^{-4}	Start: Frequency cps	Stop: Displacement in. × 10^{-4}	Stop: Frequency cps
Vertical (Z-axis)	Velocity pickup	0.9	12	0.8	12
Horizontal (X-axis)	Velocity pickup	3.3	7	3.0	7
Horizontal (Y-axis)	Accelerometer	0.6	22	0.6	22

18. These data, unlike those obtained at BAFS, exhibited a sinusoidal wave form for both starting and stopping impulses for all axes; therefore, data reduction was accomplished in the conventional manner of sinusoidal integration. Attention is again called to the fact that a small but meaningful change was made in the instrumentation used at KAFB; a displacement potentiometer was added at location 1. A second potentiometer was also placed at the first-floor level (location 3) and oriented along the X-axis. However, this transducer, lacking adequate sensitivity, did not reveal any movement at this location.

Test Series 2

BAFS

19. This series of tests was conducted in basically the same manner

as test series 1; however, in this case, the antenna was nodded and slewed simultaneously under maximum-rate conditions. Two 90-deg (0 to 90 deg and 180 to 270 deg) and two 180-deg (0 to 180 deg and 180 to 360 deg) azimuth slews were made with the transducers positioned at locations 1, 2, and 3. Table 1 shows the maximum displacements and the frequencies that occurred at each location during periods of starting and stopping the antenna. Maximum displacements again occurred at location 1, with stopping amplitudes exceeding starting movements by a factor of about 2. Average maximum values obtained during this test series at location 1 are tabulated below.

	Start		Stop	
Orientation	Displacement in. $\times 10^{-4}$	Frequency cps	Displacement in. $\times 10^{-4}$	Frequency cps
Vertical (Z-axis)	22.5	20	49.8	20
Horizontal (X-axis)	66.0	--	111.3	7
Horizontal (Y-axis)	45.0	20	79.4	20

20. A comparison of these data and those acquired during the conduct of test 1 shows a remarkable similarity. Thus, on the basis of such a comparison, it was concluded that nodding the antenna while performing the slewing operation had little, if any, significant influence on maximum movements of the antenna support structure. It was also noted that the movements incurred by the support pedestal were not significantly influenced by the starting position, the stopping position, or the total number of degrees traveled by the antenna. Therefore, it was considered feasible to average all data collected during slewing operations of the antenna. The arithmetic averages of the displacement data obtained from both tests 1 and 2 are presented in table 3. These average maximum displacements were used to graphically illustrate the instrumented column movement in the X-Z and X-Y planes without respect to phase relations so that a direct comparison of starting and stopping impulses could be made. These movements are shown in plates 6 and 7. As indicated in the graphic plots, the clockwise rotation of the antenna caused the support pedestal to respond to a starting impulse by rebounding in a counterclockwise direction, while the initial force translated to the structure by the antenna coming to a complete stop caused a clockwise response.

KAFB

21. Tests at KAFB in this series were conducted in the same manner as at BAFS. Two 180-deg (0 to 180 deg and 180 to 360 deg) azimuth slews were conducted with pickups positioned at locations 1, 2, and 3. The transducers were then repositioned in locations 1, 2, and 4, and tests were made with the antenna slewing through 45 deg (0 to 45 deg), 90 deg (0 to 90 deg and 180 to 270 deg), and 180 deg (0 to 180 deg and 180 to 360 deg). Table 2 shows displacements and frequencies recorded at each location during antenna starting and stopping modes. Average maximum displacements occurring at location 1 and their associated frequencies were as follows:

		Start		Stop	
Orientation	Transducer	Displacement in. $\times 10^{-4}$	Frequency cps	Displacement in. $\times 10^{-4}$	Frequency cps
Vertical (Z-axis)	Velocity pickup	16.6	12	29.7	12
Horizontal (X-axis)	Velocity pickup	53.5	7	101.1	7
Horizontal (X-axis)	Potentiometer	68.1	7	138.8	7
Horizontal (Y-axis)	Accelerometer	12.7	22	26.3	22

Average displacements recorded at location 4, the foundation footing, showed virtually the same movements for antenna starts and stops as indicated in the following tabulation:

		Start		Stop	
Orientation	Transducer	Displacement in. $\times 10^{-4}$	Frequency cps	Displacement in. $\times 10^{-4}$	Frequency cps
Vertical (Z-axis)	Velocity pickup	1.0	12	0.8	12
Horizontal (X-axis)	Velocity pickup	2.8	7	3.1	7
Horizontal (Y-axis)	Accelerometer	0.5	22	0.5	22

22. As was discussed for the BAFS tests, a strong similarity was found between the data obtained in these tests and the data acquired during the conduct of test 1. Therefore, one could conclude that nodding the

antenna produced no significant change in structure movement at the Keesler site. These data were averaged with test 1 data and are presented in table 4. These data, again exhibiting excellent similarities, were then averaged to include all azimuth slews without regard to starting position, stopping position, or number of degrees traveled by the antenna. The data are presented in plates 8 and 9, which graphically portray movements along the X-Z and X-Y planes, respectively, without regard to phase relation. The KAFB tower also rebounded in a counterclockwise direction when the antenna started in a clockwise direction, and reacted in a clockwise movement when the antenna decelerated rapidly to a complete stop.

Test Series 3

BAFS

23. This series of tests was conducted for observational rather than analytical interest. In these tests the antenna was positioned at various points referenced to the instrumented 0-deg column and the antenna sail was nodded under maximum conditions without any slewing component. The test was conducted at the 0-deg azimuth point with the transducers in locations 1, 2, and 3, and was repeated at the 0-, 45-, and 90-deg positions with the transducers in locations 1, 3, and 4. Frequencies determined for the X-, Y-, and Z-axes were 12, 10, and 10 cps, respectively, for all test runs. Displacements are shown in table 1. These values showed variation for each antenna position; therefore, it was not deemed feasible to combine these data. It is interesting to note that the vertical (Z) axis showed extremely small movements (seemingly independent of antenna position) as compared to the X- and Y-axes which varied considerably with antenna orientation.

KAFB

24. The series 3 tests at KAFB were conducted in the same manner as at the BAFS site. Transducers remained in locations 1, 2, and 4 for antenna nodding runs at the 0-, 90-, and 180-deg positions. Frequencies along all axes were approximately 20 cps, which is double those for the BAFS structure. This can possibly be attributed to the inherently stiffer structure design caused by the 25-ft shorter antenna support pedestal.

Displacement data, which were consistent with antenna location, are shown in table 2.

Time-Phase Relation Analysis

BAFS

25. The stopping displacements only were used to portray the bending movements incurred by the instrumented column, since amplitudes and recorded wave shapes of the structure's response were the most conducive to analysis. The limited number of available transducers having nearly identical phase characteristics had been placed to measure movement along the X-axis of the instrumented column and footing. Therefore, only the X-axis (which received the greatest torque) could be accurately analyzed with respect to displacement at a given time. Plate 10 shows the time-phase relation between given locations on the instrumented antenna support column. Considering the time at which the antenna stopped immediately prior to structure movement as zero, at an elapsed time of 36 msec, the transducer at location 1 had reached its maximum value for movement in the clockwise direction while the transducer at location 2 had moved only slightly in the same direction, and the transducer at location 3 had not yet received an impulse. At 30 msec later, i.e. at an elapsed time of 66 msec, the transducer at location 2 had reached its peak displacement, while the instrument at location 1 had reversed direction, passed zero, and had continued toward its second peak. Location 3, at this time, had not yet experienced any movement. At an elapsed time of 96 msec, the transducer at location 3 reached maximum displacement while those at locations 1 and 2 were in positions shown in plate 10. It should again be noted that no vertical movements are shown because no reliable phase correlation can be made between these pickups and the type of pickup used to monitor X-axis movements.

KAFB

26. In exactly the same manner as described for BAFS, plate 11 shows the time-phase relation of movements incurred by the instrumented column at KAFB. The structure response was quite similar to that of the BAFS antenna pedestal.

Discussion

27. The data obtained at BAFS were utilized in a brief theoretical analysis to determine the realistic significance of the displacements, phase relations, and frequencies measured. Two approaches, the Reissner-Sung theory* and a model system consisting of a weighted spring, mass, and dashpot were used. Presentation of this analysis is considered to be beyond the scope of this report, since theoretical evaluation and design criteria are primarily the responsibility of ORDL. ORDL is at present formulating a report that will include a comprehensive analysis of the FPS-26 radar towers. However, the analysis conducted by WES did seem to establish a relation between torsional movements and the recorded frequency range of 18 to 22 cps, the rocking mode and the 7-cps recorded frequency, and the relation of the sliding mode to the 12-cps frequency. The displacement data appeared reasonable, and the time-phase relations were considered to be entirely feasible.

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* Sung, T. Y., "Vibrations in semi-infinite solids due to periodic surface loading," Symposium on Dynamic Testing of Soils, American Society for Testing Materials, Special Technical Publication No. 156 (Philadelphia, Pa., July 1953), pp 35-68.

PART IV: CONCLUSIONS

28. This study was conducted to determine the structure response of the FPS-26 radar towers located at BAFS and KAFB resulting from antenna operation. It was concluded that the mechanical performance of the antenna at each site was virtually identical with respect to acceleration, maximum velocity, and deceleration rates. These rates were determined from tachometer recordings to be: (a) acceleration 1.14 radians per sec^2, (b) maximum velocity 1.35 radians per sec, and (c) deceleration 2.52 radians per sec^2. From the displacement data obtained at BAFS, it was concluded that the antenna pedestal level (location 1) experienced the greatest movements in the axis parallel to applied torque. The average maximum movement occurring at this location was 114.2×10^{-4} in. The foundation footing, which was of primary importance, displaced only an average of 6.2×10^{-4} in. The KAFB tower responded to similar antenna loadings in the same respective locations with movements of 126.5 and 3.2×10^{-4} in. The conclusion was also reached that movements resulting from antenna stops exceeded starting movements by a factor of about 2 at both towers. From the azimuth data obtained, it was also concluded that nodding the antenna while slewing produced no appreciable effect on wave shapes or measured displacements. Phase-relation analysis of the structures revealed that the towers responded to antenna starting movements in the clockwise direction by rebounding in a counterclockwise direction; the structures then recovered. When the antenna came to a complete stop, inertial effects caused the towers to continue twisting in a clockwise direction. Vertical transducers also indicated that the structures shortened while twisting.

29. It was concluded from theoretical analysis of the data, using the BAFS tower as a model reference, that the 7-cps frequency predominant along the X-axis was indicative of the natural frequency of the system in the rocking mode. The 20 cps recorded along the Y-axis was the natural frequency of the torsional mode and the 12 cps recorded along the vertical Z-axis represented natural frequency of the sliding mode.

Test No.	Location No.	Transducer			Slew 0 to 90°						Slew 180 to 270°			
					Starting			Stopping			Starting			St
					Displacement			Displacement			Displacement			Displace
		Number	Orientation	Axis	Inches $\times 10^{-4}$	mils	Frequency cps*	Inches $\times 10^{-4}$	mils	Frequency cps	Inches $\times 10^{-4}$	mils	Frequency cps*	Inches $\times 10^{-4}$
1 (Slew only)	1	1	Vertical	Z	26.4	---	20	49.8	---	20	33.3	---	20	45.6
		2	Horizontal	X	79.0	0.099	(20)	114.0	0.143	7	75.5	0.094	(20)	124.0
		3	Horizontal	Y	33.9	---	20	143.3	---	20	102.7	---	20	123.3
	2	4	Vertical	Z	1.0	---	20	5.2	---	20	2.6	---	20	3.1
		5	Horizontal	X	19.1	0.024	(20)	48.7	0.061	7	27.2	0.034	(20)	68.3
		6	Horizontal	Y	1.4	---	20	4.0	---	20	3.2	---	20	3.2
	3	7	Vertical	Z	0.4	---	20	3.2	---	20	1.5	---	20	1.6
		8	Horizontal	X	2.7	0.003	(20)	6.3	0.008	7	2.7	0.003	(20)	12.6
		9	Horizontal	Y	0.6	---	20	4.5	---	20	1.1	---	20	1.9
	1	1	Vertical	Z	41.5	---	20	49.8	---	20	28.0	---	20	37.3
		2	Horizontal	X	105.0	0.131	(20)	114.0	0.142	7	69.8	0.087	(20)	171.0
		3	Horizontal	Y	62.4	---	20	102.4	---	20	61.6	---	20	71.7
	3	7	Vertical	Z	0.3	---	20	1.0	---	20	0.4	---	20	0.1
		8	Horizontal	X	3.3	0.004	(20)	2.5	0.003	7	3.8	0.005	(20)	7.5
		9	Horizontal	Y	1.0	---	20	2.3	---	20	0.5	---	20	1.2
	4	10	Vertical	Z	0.3	---	20	0.2	---	20	2.1	---	20	0.5
		11	Horizontal	X	2.3	0.003	(20)	1.3	0.002	7	1.7	0.002	(20)	9.2
		12	Horizontal	Y	0.8	---	20	1.4	---	20	0.3	---	20	2.3
2 (Slew & nod)	1	1	Vertical	Z	21.6	---	20	49.8	---	20	27.4	---	20	49.8
		2	Horizontal	X	59.8	0.075	(20)	107.0	0.134	7	75.5	0.094	(20)	117.0
		3	Horizontal	Y	38.7	---	20	123.1	---	20	51.3	---	20	113.1
	2	4	Vertical	Z	1.0	---	20	2.6	---	20	1.6	---	20	1.0
		5	Horizontal	X	26.0	0.032	(20)	46.0	0.058	7	39.3	0.049	(20)	69.7
		6	Horizontal	Y	8.9	---	20	2.6	---	20	3.0	---	20	2.0
	3	7	Vertical	Z	0.3	---	20	0.6	---	20	0.5	---	20	0.3
		8	Horizontal	X	2.7	0.003	(20)	3.8	0.005	7	1.6	0.002	(20)	2.5
		9	Horizontal	Y	0.5	---	20	0.2	---	20	0.3	---	20	1.0
3 (Nod only)	1	1	Vertical	Z										
		2	Horizontal	X										
		3	Horizontal	Y										
	2	4	Vertical	Z										
		5	Horizontal	X										
		6	Horizontal	Y										
	3	7	Vertical	Z										
		8	Horizontal	X										
		9	Horizontal	Y										
	1	1	Vertical	Z										
		2	Horizontal	X										
		3	Horizontal	Y										
	3	7	Vertical	Z										
		8	Horizontal	X										
		9	Horizontal	Y										
	4	10	Vertical	Z										
		11	Horizontal	X										
		12	Horizontal	Y										

Note: One mil equals 10^{-3} radians.
* Values in parentheses are time in milliseconds, as explained in paragraph 15 of the text.

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Table 1

Maximum Displacement Determinations, BAFS

Slew 180 to 270°						Slew 0 to 180°						Slew 180 to 360°				
Starting			Stopping			Starting			Stopping			Starting			Stopping	
Displacement Inches × 10^{-4}	Displacement mils	Frequency cps*	Displacement Inches × 10^{-4}	Displacement mils	Frequency cps	Displacement Inches × 10^{-4}	Displacement mils	Frequency cps*	Displacement Inches × 10^{-4}	Displacement mils	Frequency cps	Displacement Inches × 10^{-4}	Displacement mils	Frequency cps*	Displacement Inches × 10^{-4}	Displacement mils
33.3	---	20	45.6	---	20	19.8	---	20	49.8	---	20	45.6	---	20	49.8	---
75.5	0.094	(20)	124.0	0.155	7	62.8	0.078	(20)	114.0	0.143	7	100.5	0.126	(20)	121.0	0.126
102.7	---	20	123.3	---	20	46.3	---	20	143.3	---	20	71.9	---	20	123.2	---
2.6	---	20	3.1	---	20	1.6	---	20	3.2	---	20	3.7	---	20	2.5	---
27.2	0.034	(20)	68.3	0.085	7	17.8	0.022	(20)	46.0	0.058	7	37.6	0.047	(20)	36.8	0.046
3.2	---	20	3.2	---	20	1.4	---	20	2.6	---	20	3.6	---	20	2.6	---
1.5	---	20	1.6	---	20	0.4	---	20	1.9	---	20	1.0	---	20	1.3	---
2.7	0.003	(20)	12.6	0.016	7	1.6	0.002	(20)	6.3	0.008	7	3.8	0.005	(20)	3.8	0.005
1.1	---	20	1.9	---	20	0.7	---	20	1.5	---	20	1.0	---	20	2.0	---
28.0	---	20	37.3	---	20	20.8	---	20	62.2	---	20	10.8	---	20	22.8	---
69.8	0.087	(20)	171.0	0.214	7	59.8	0.075	(20)	110.0	0.138	7	41.5	0.052	(20)	57.2	0.072
61.6	---	20	71.7	---	20	25.6	---	20	102.7	---	20	49.6	---	20	40.9	---
0.4	---	20	0.1	---	20	0.3	---	20	1.3	---	20	0.1	---	20	---	---
3.8	0.005	(20)	7.5	0.009	7	2.7	0.003	(20)	8.8	0.011	7	2.7	0.003	(20)	5.0	0.006
0.5	---	20	1.2	---	20	0.6	---	20	2.4	---	20	1.1	---	20	0.2	---
2.1	---	20	0.5	---	20	0.2	---	20	0.7	---	20	0.7	---	20	4.3	---
1.7	0.002	(20)	9.2	0.012	7	1.7	0.002	(20)	5.2	0.006	7	4.0	0.005	(20)	9.2	0.012
0.3	---	20	2.3	---	20	0.3	---	20	1.4	---	20	1.0	---	20	3.5	---
27.4	---	20	49.8	---	20	14.5	---	20	49.8	---	20	26.6	---	20	49.8	---
75.5	0.094	(20)	117.0	0.146	7	56.6	0.071	(20)	121.0	0.151	7	72.3	0.090	(20)	100.0	0.125
51.3	---	20	113.1	---	20	51.3	---	20	102.7	---	20	34.7	---	20	102.7	---
1.6	---	20	1.0	---	20	0.5	---	20	2.1	---	20	2.4	---	20	2.1	---
39.3	0.049	(20)	65.7	0.082	7	20.2	0.025	(20)	48.6	0.061	7	34.7	0.043	(20)	34.2	0.043
3.0	---	20	2.0	---	20	2.2	---	20	1.9	---	20	2.3	---	20	2.3	---
0.5	---	20	0.3	---	20	0.1	---	20	0.6	---	20	0.3	---	20	0.6	---
1.6	0.002	(20)	2.5	0.003	7	2.2	0.003	(20)	6.3	0.008	7	2.7	0.003	(20)	2.5	0.003
0.3	---	20	1.0	---	20	0.5	---	20	1.3	---	20	2.6	---	20	1.0	---

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Frequency cps	Slew 180 to 360° Starting Displacement Inches × 10^{-4}	Starting Displacement mils	Starting Frequency cps*	Stopping Displacement Inches × 10^{-4}	Stopping Displacement mils	Stopping Frequency cps	Nodding at 0° Displacement Inches × 10^{-4}	Nodding at 0° Displacement mils	Nodding at 0° Frequency cps	Nodding at 45° Displacement Inches × 10^{-4}	Nodding at 45° Displacement mils	Nodding at 45° Frequency cps	Nodding at 90° Displacement Inches × 10^{-4}	Nodding at 90° Displacement mils	Nodding at 90° Frequency cps
20	45.6	---	20	49.8	---	20									
7	100.5	0.126	(20)	121.0	0.126	7									
20	71.9	---	20	123.2	---	20									
20	3.7	---	20	2.5	---	20									
7	37.6	0.047	(20)	36.8	0.046	7									
20	3.6	---	20	2.6	---	20									
20	1.0	---	20	1.3	---	20									
7	3.8	0.005	(20)	3.8	0.005	7									
20	1.0	---	20	2.0	---	20									
20	10.8	---	20	22.8	---	20									
7	41.5	0.052	(20)	57.2	0.072	7									
20	49.6	---	20	40.9	---	20									
20	0.1	---	20	---	---	--									
7	2.7	0.003	(20)	5.0	0.006	7									
20	1.1	---	20	0.2	---	20									
20	0.7	---	20	[illegible]	---	20									
7	4.0	0.005	(20)	[illegible]	0.012	7									
20	1.0	---	20	3.5	---	20									
20	26.6	---	20	49.8	---	20									
7	72.3	0.090	(20)	100.0	0.125	7									
20	38.7	---	20	102.7	---	20									
20	2.4	---	20	2.1	---	20									
7	34.7	0.043	(20)	34.2	0.043	7									
20	2.3	---	20	2.3	---	20									
20	0.3	---	20	0.6	---	20									
7	2.7	0.003	(20)	2.5	0.003	7									
20	0.6	---	20	1.0	---	20									
							4.2	---	10						
							4.8	0.006	12						
							25.6	---	10						
							0.8	---	10						
							16.2	0.020	12						
							4.4	---	10						
							--	---	--						
							--	---	--						
							--	---	--						
							4.2	---	10	--	---	--	3.4	---	10
							4.5	0.006	12	6.0	0.008	12	11.9	0.015	12
							22.6	---	10	39.0	---	10	12.3	---	10
							0.9	---	10	1.4	---	10	1.4	---	10
							--	---	--	--	---	--	2.4	0.003	12
							--	---	--	--	---	--	--	---	--
							1.1	---	10	2.0	---	10	3.0	---	10
							1.4	0.002	12	1.4	0.002	12	1.4	0.002	12
							2.4	---	10	--	---	--	--	---	--

Test No.	Location No.	Transducer			Slew 0 to 45°						Sle		
					Starting			Stopping			Starting		
					Displacement		Frequency cps	Displacement		Frequency cps	Displacement		Fr que cp
		Number	Orientation	Axis	Inches $\times 10^{-4}$	mils		Inches $\times 10^{-4}$	mils		Inches $\times 10^{-4}$	mils	
1 (Slew only)	1	1	Vertical	Z									
		2	Horizontal	X									
		Pot.*	Horizontal	X									
		3	Horizontal	Y									
	2	4	Vertical	Z									
		5	Horizontal	X									
		6	Horizontal	Y									
	3	7	Vertical	Z									
		8	Horizontal	X									
		9	Horizontal	Y									
	1	1	Vertical	Z	15.5	---	12	59.4	---	12	36.4	---	12
		2	Horizontal	X	79.8	0.100	7	172.0	0.215	7	57.0	0.071	7
		Pot.	Horizontal	X	73.0	0.091	7	132.5	0.166	7	67.5	0.084	7
		3	Horizontal	Y	8.3	---	22	11.6	---	22	8.3	---	22
	2	4	Vertical	Z	4.2	---	12	5.8	---	12	6.7	---	12
		5	Horizontal	X	16.9	0.021	7	19.6	0.024	7	31.2	0.039	7
		6	Horizontal	Y	4.2	---	22	3.7	---	22	3.4	---	22
	4	10	Vertical	Z	1.2	---	12	1.0	---	12	1.0	---	12
		11	Horizontal	X	---	---	--	2.5	0.003	7	4.9	0.006	7
		12	Horizontal	Y	0.4	---	22	0.4	---	22	1.0	---	22
2 (Slew & nod)	1	1	Vertical	Z									
		2	Horizontal	X									
		Pot.	Horizontal	X									
		3	Horizontal	Y									
	2	4	Vertical	Z									
		5	Horizontal	X									
		6	Horizontal	Y									
	3	7	Vertical	Z									
		8	Horizontal	X									
		9	Horizontal	Y									
	1	1	Vertical	Z	63.8	---	12	50.2	---	12	27.4	---	12
		2	Horizontal	X	102.5	0.128	7	105.4	0.132	7	85.5	0.107	7
		Pot.	Horizontal	X	71.2	0.089	7	96.0	0.120	7	71.2	0.089	7
		3	Horizontal	Y	25.0	---	22	13.6	---	22	7.5	---	22
	2	4	Vertical	Z	8.8	---	12	6.7	---	12	6.3	---	12
		5	Horizontal	X	15.6	0.020	7	46.8	0.058	7	26.0	0.032	7
		6	Horizontal	Y	8.6	---	22	4.9	---	22	3.4	---	22
	4	10	Vertical	Z	1.9	---	12	1.0	---	12	1.0	---	12
		11	Horizontal	X	2.5	0.003	7	2.5	0.003	7	3.7	0.005	7
		12	Horizontal	Y	0.7	---	22	0.7	---	22	0.6	---	22
3 (Nod only)	1	1	Vertical	Z									
		2	Horizontal	X									
		3	Horizontal	Y									
	2	4	Vertical	Z									
		5	Horizontal	X									
		6	Horizontal	Y									
	4	10	Vertical	Z									
		11	Horizontal	X									
		12	Horizontal	Y									

Note: One mil equals 10^{-3} radians.
* Potentiometer.

Table 2

Maximum Displacement Determinations, KAFB

	Slew 0 to 90°						Slew 180 to 270°						Slew 0 to 18			
	Starting			Stopping			Starting			Stopping			Starting			
	Displacement			Displacement			Displacement			Displacement			Displacement			Dis
Fre-quency cps	Inches x 10^{-4}	mils	Fre-quency cps	Inches x 10^{-4}	mils	Fre-quency cps	Inches x 10^{-4}	mils	Fre-quency cps	Inches x 10^{-4}	mils	Fre-quency cps	Inches x 10^{-4}	mils	Fre-quency cps	Inc x 1
													10.5	---	12	24.
													57.0	0.071	7	85.
													67.5	0.084	7	146.
													20.8	---	22	41.
													3.8	---	12	2.
													32.5	0.041	7	80.
													1.2	---	22	3.
													1.4	---	12	1.
													6.2	0.008	7	12.
													0.6	---	22	0.
12	36.4	---	12	50.2	---	12	14.6	---	12	38.8	---	12	13.7	---	12	32.
7	57.0	0.071	7	166.0	0.208	7	37.0	0.046	7	91.3	0.114	7	42.7	0.053	7	99.
7	67.5	0.084	7	132.5	0.166	7	97.0	0.121	7	187.0	0.234	7	47.5	0.059	7	155.
22	8.3	---	22	14.2	---	22	8.3	---	22	10.0	---	22	3.3	---	22	8.
12	6.7	---	12	7.5	---	12	2.1	---	12	6.2	---	12	1.0	---	12	2.
7	31.2	0.039	7	65.0	0.081	7	19.5	0.024	7	39.0	0.049	7	13.0	0.016	7	84.
22	3.4	---	22	5.7	---	22	1.4	---	22	2.6	---	22	1.7	---	22	2.
12	1.0	---	12	0.8	---	12	1.0	---	12	1.0	---	12	0.4	---	12	0.
7	4.9	0.006	7	2.5	0.003	7	2.5	0.003	7	2.5	0.003	7	2.5	0.003	7	2.
22	1.0	---	22	0.8	---	22	0.4	---	22	0.7	---	22	0.2	---	22	0.
													6.8	---	12	21.
													48.4	0.060	7	96.
													50.2	0.063	7	128.
													29.2	---	22	41.
													3.1	---	12	4.
													26.0	0.032	7	82.
													0.6	---	22	4.
													1.0	---	12	2.
													6.8	0.008	7	12.
													0.8	---	22	0.
12	27.4	---	12	48.4	---	12	16.9	---	12	27.4	---	12	32.0	---	12	31.
7	85.5	0.107	7	131.0	0.164	7	28.5	0.036	7	114.0	0.142	7	37.0	0.046	7	128.
7	71.2	0.089	7	137.0	0.132	7	91.3	0.114	7	208.0	0.260	7	50.1	0.063	7	151.
22	7.5	---	22	13.3	---	22	11.6	---	22	25.0	---	22	5.0	---	22	11.
12	6.3	---	12	7.3	---	12	2.9	---	12	3.8	---	12	2.1	---	12	1.
7	26.0	0.032	7	84.5	0.106	7	10.4	0.013	7	52.0	0.065	7	26.0	0.032	7	65.
22	3.4	---	22	3.7	---	22	3.7	---	22	2.9	---	22	2.6	---	22	1.
12	1.0	---	12	1.2	---	12	1.0	---	12	---	---	--	1.0	---	12	0.
7	3.7	0.005	7	3.7	0.005	7	2.5	0.003	7	3.7	0.005	7	2.5	0.003	7	2.
22	0.6	---	22	1.0	---	22	0.4	---	22	0.5	---	22	0.3	---	22	0.

18.2

...ing	Slew 180 to 360°						Nodding at 0°			Nodding at 90°			Nodding at 180°		
	Starting			Stopping											
	Displacement			Displacement			Displacement			Displacement			Displacement		
Frequency cps	Inches × 10^{-4}	mils	Frequency cps	Inches × 10^{-4}	mils	Frequency cps	Inches × 10^{-4}	mils	Frequency cps	Inches × 10^{-4}	mils	Frequency cps	Inches × 10^{-4}	mils	Frequency cps
12	20.2	---	12	25.5	---	12									
7	42.7	0.053	7	71.2	0.089	7									
7	42.0	0.053	7	95.0	0.119	7									
22	33.3	---	22	37.4	---	22									
12	3.5	---	12	3.8	---	12									
7	39.0	0.049	7	45.5	0.057	7									
22	0.6	---	22	4.0	---	22									
12	2.7	---	12	1.6	---	12									
7	9.5	0.012	7	12.3	0.015	7									
22	1.1	---	22	0.8	---	22									
12	5.0	---	12	41.1	---	12									
7	57.0	0.071	7	99.7	0.125	7									
7	75.0	0.094	7	114.0	0.142	7									
22	3.3	---	22	10.0	---	22									
12	1.2	---	12	2.1	---	12									
7	26.0	0.032	7	31.2	0.039	7									
22	0.6	---	22	2.0	---	22									
12	--	---	--	0.8	---	12									
7	--	---	--	5.0	0.006	7									
22	1.1	---	22	0.4	---	22									
12	13.7	---	12	27.4	---	12									
7	71.2	0.089	7	65.5	0.082	7									
7	73.0	0.091	7	96.0	0.120	7									
22	8.3	---	22	41.6	---	22									
12	3.1	---	12	2.1	---	12									
7	29.9	0.037	7	39.0	0.049	7									
22	1.4	---	22	4.3	---	22									
12	1.2	---	12	1.5	---	12									
7	6.8	---	7	8.7	0.011	7									
22	0.6	---	22	0.8	---	22									
12	3.6	---	12	21.9	---	12									
7	51.2	0.064	7	71.2	0.089	7									
7	73.0	0.091	7	113.0	0.141	7									
22	15.0	---	22	25.0	---	22									
12	1.7	---	12	2.9	---	12									
7	28.6	0.036	7	61.2	0.076	7									
22	1.7	---	22	4.3	---	22									
12	0.2	---	12	---	---	--									
7	--	---	7	---	---	--									
22	0.4	---	22	0.1	---	22									
							2.8	---	20	2.3	---	20	4.6	---	20
							5.5	0.007	20	6.0	0.008	20	6.5	0.008	20
							---	---	--	---	---	--	---	---	--
							0.4	---	20	0.2	---	20	0.2	---	20
							2.3	0.003	20	2.1	0.003	20	2.3	0.003	20
							---	---	--	---	---	--	---	---	--
							0.2	---	20	0.2	---	20	0.2	---	20
							0.4	0.0005	20	0.4	0.0005	20	0.4	0.0005	20
							0.03	---	20	0.03	---	20	0.03	---	20

Table 3

Average Maximum Displacements, Tests 1 and 2, BAFS

Location No.	Slew in deg	Displacement, in. $\times 10^{-4}$: Vertical Z-Axis Starting	Vertical Z-Axis Stopping	Horizontal* X-Axis Starting	Horizontal* X-Axis Stopping	Horizontal Y-Axis Starting	Horizontal Y-Axis Stopping
1	0- 90	29.8	49.8	81.3(0.102)	111.7(0.140)	45.0	122.9
	180-270	29.6	44.2	73.6(0.092)	137.3(0.172)	71.9	102.7
	0-180	18.4	53.9	59.7(0.075)	115.0(0.144)	41.1	116.2
	180-360	27.7	40.8	71.4(0.089)	92.7(0.116)	53.4	88.9
	Avg	26.4	47.2	71.5(0.090)	114.2(0.143)	52.8	107.7
2	0- 90	1.0	3.9	22.6(0.028)	47.4(0.059)	5.0	3.3
	180-270	2.1	2.0	33.2(0.042)	67.0(0.084)	3.1	2.6
	0-180	1.0	2.6	19.0(0.024)	47.3(0.059)	1.8	2.2
	180-360	3.0	2.3	36.2(0.045)	35.5(0.044)	3.0	2.4
	Avg	1.8	2.7	27.8(0.035)	49.3(0.062)	3.2	2.6
3	0- 90	0.3	1.6	2.9(0.004)	4.2(0.005)	0.7	2.3
	180-270	0.8	0.7	2.7(0.003)	7.5(0.009)	0.7	1.4
	0-180	0.3	1.6	2.2(0.003)	7.1(0.009)	0.6	1.4
	180-360	0.5	1.0	3.1(0.004)	3.8(0.005)	0.9	1.1
	Avg	0.5	1.2	2.7(0.004)	5.6(0.007)	0.7	1.6
4	0- 90	0.3	0.2	2.3(0.003)	1.3(0.002)	0.8	1.4
	180-270	2.1	0.5	1.7(0.002)	9.2(0.012)	0.3	2.3
	0-180	0.2	0.7	1.7(0.002)	5.2(0.006)	0.3	1.4
	180-360	0.7	4.3	4.0(0.005)	9.2(0.012)	1.0	3.5
	Avg	0.8	1.4	2.4(0.003)	6.2(0.008)	0.6	2.2

* Values in parentheses are displacement in mils. A mil equals 10^{-3} radians.

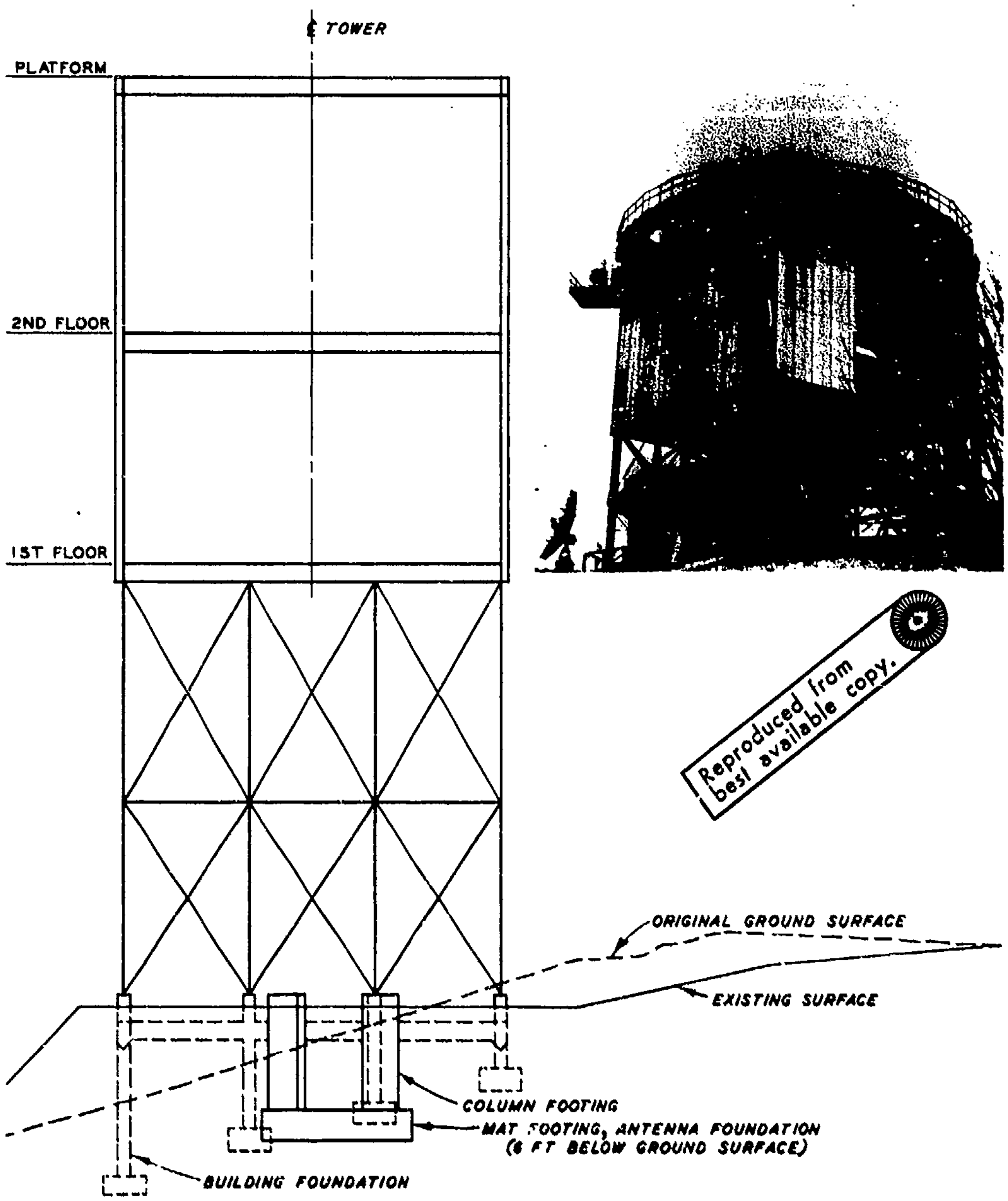
Table 4

Average Maximum Displacements, Tests 1 and 2, KAFB

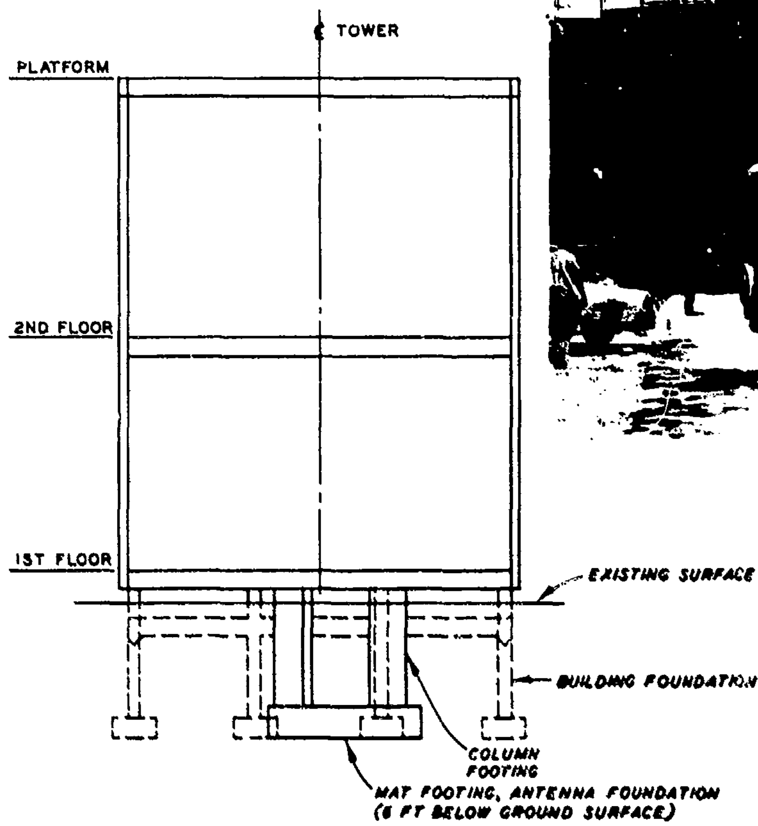
Location No.	Slew in deg	Displacement, in. $\times 10^{-4}$ Vertical Z-Axis Starting	Vertical Z-Axis Stopping	Horizontal* X-Axis Starting	Horizontal* X-Axis Stopping	Horizontal Y-Axis Starting	Horizontal Y-Axis Stopping
1**	0- 45	39.6	54.8	81.6(0.102)	126.5(0.158)	16.6	12.6
	0- 90	31.9	49.3	70.3(0.088)	141.6(0.177)	7.9	13.8
	180-270	15.8	33.1	63.5(0.079)	150.1(0.188)	10.0	17.5
	0-180	15.8	27.4	50.0(0.062)	123.8(0.154)	14.6	25.8
	180-360	10.6	29.0	60.6(0.076)	90.7(0.113)	15.0	28.5
	Avg	22.7	38.7	65.2(0.081)	126.5(0.158)	12.8	19.6
2	0- 45	6.5	6.2	16.2(0.020)	33.2(0.042)	6.4	4.3
	0- 90	6.5	7.4	28.6(0.036)	74.8(0.094)	3.4	4.7
	180-270	2.5	5.0	15.0(0.019)	45.5(0.057)	2.6	2.8
	0-180	2.5	2.8	24.4(0.030)	78.0(0.098)	1.5	2.8
	180-360	2.4	2.7	30.9(0.039)	44.2(0.055)	1.1	3.6
	Avg	4.1	4.8	23.0(0.029)	55.1(0.069)	3.0	3.6
3	0-180	1.2	2.1	6.5(0.008)	12.6(0.016)	0.7	0.6
	180-360	2.0	1.6	8.2(0.010)	10.5(0.013)	0.8	0.8
	Avg	1.6	1.8	7.4(0.009)	11.6(0.014)	0.8	0.7
4	0- 45	1.6	1.0	2.5(0.003)	2.5(0.003)	0.6	0.6
	0- 90	1.0	1.0	4.3(0.005)	2.9(0.004)	0.8	0.9
	180-270	1.0	1.0	2.5(0.003)	3.1(0.004)	0.4	0.6
	0-180	1.0	1.2	2.5(0.003)	2.5(0.003)	0.2	0.4
	180-360	1.4	1.3	--	5.0(0.006)	0.8	0.2
	Avg	1.2	1.0	3.0(0.004)	3.2(0.004)	0.6	0.5

* Values in parentheses are displacement in mils. A mil equals 10^{-3} radians.

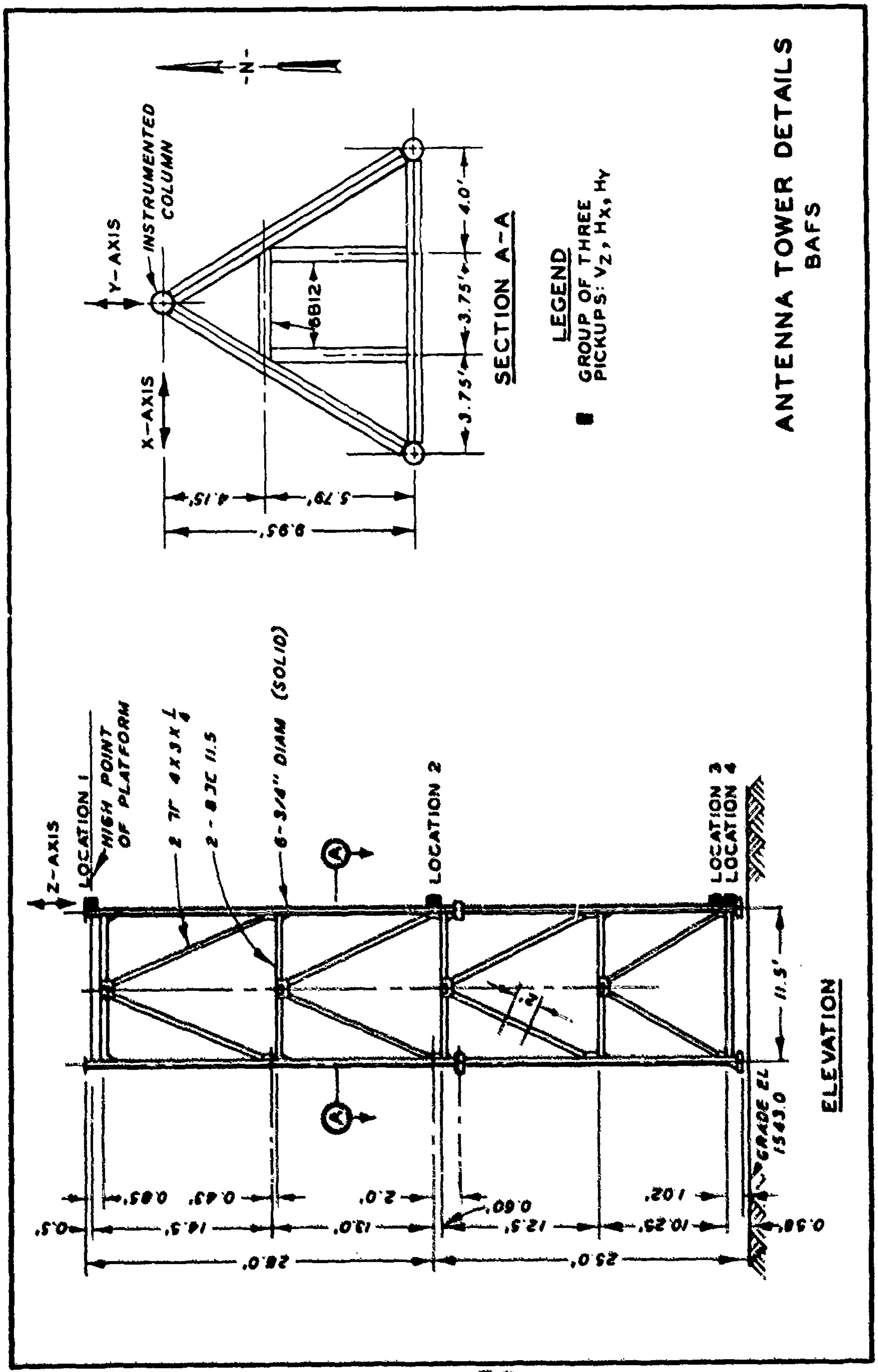
** Data for location 1 include potentiometer measurements.



OUTER STRUCTURE DETAILS
FPS-26 TOWER, BAFS

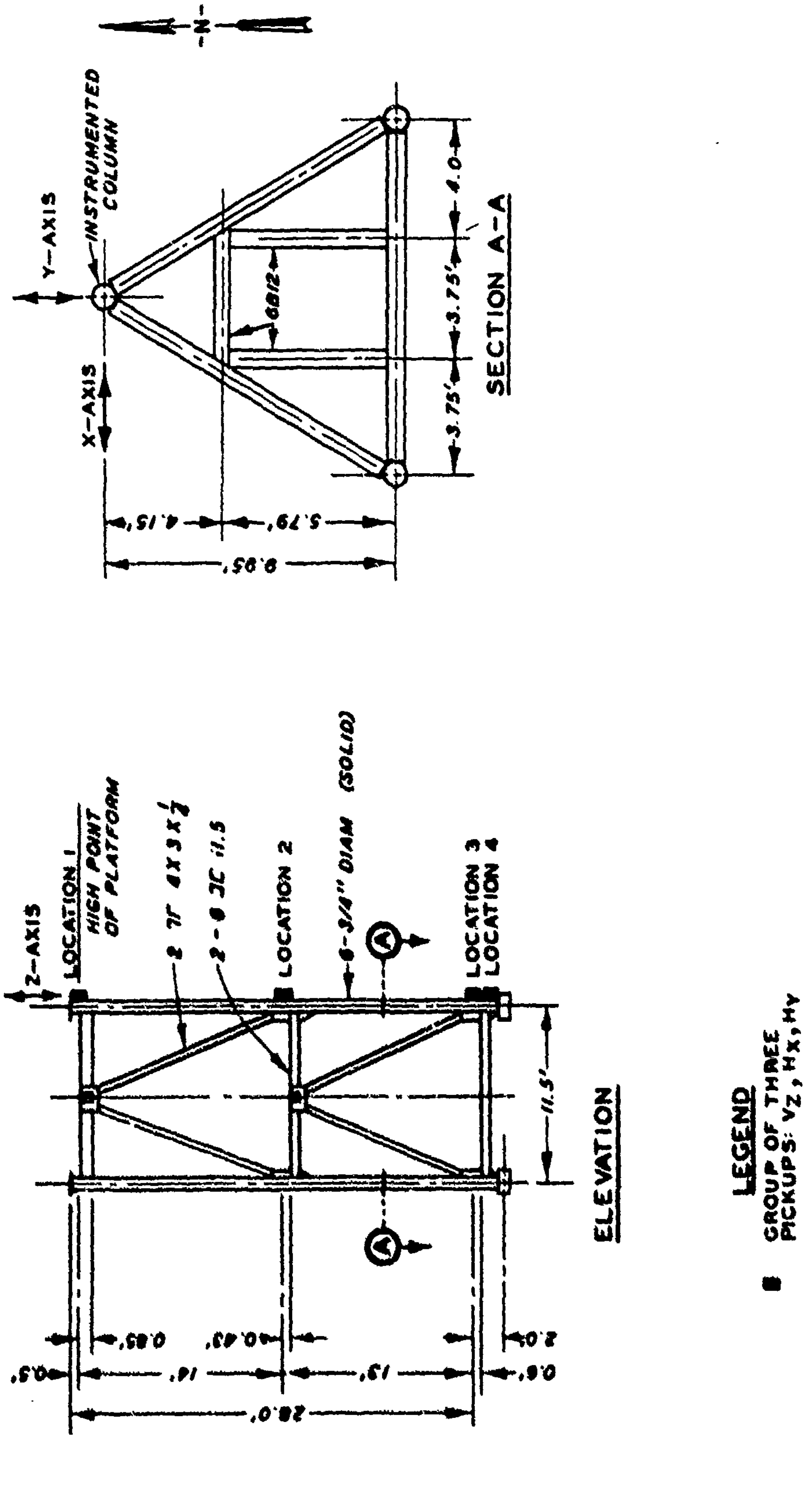


OUTER STRUCTURE DETAILS
FPS-26 TOWER, KAFB



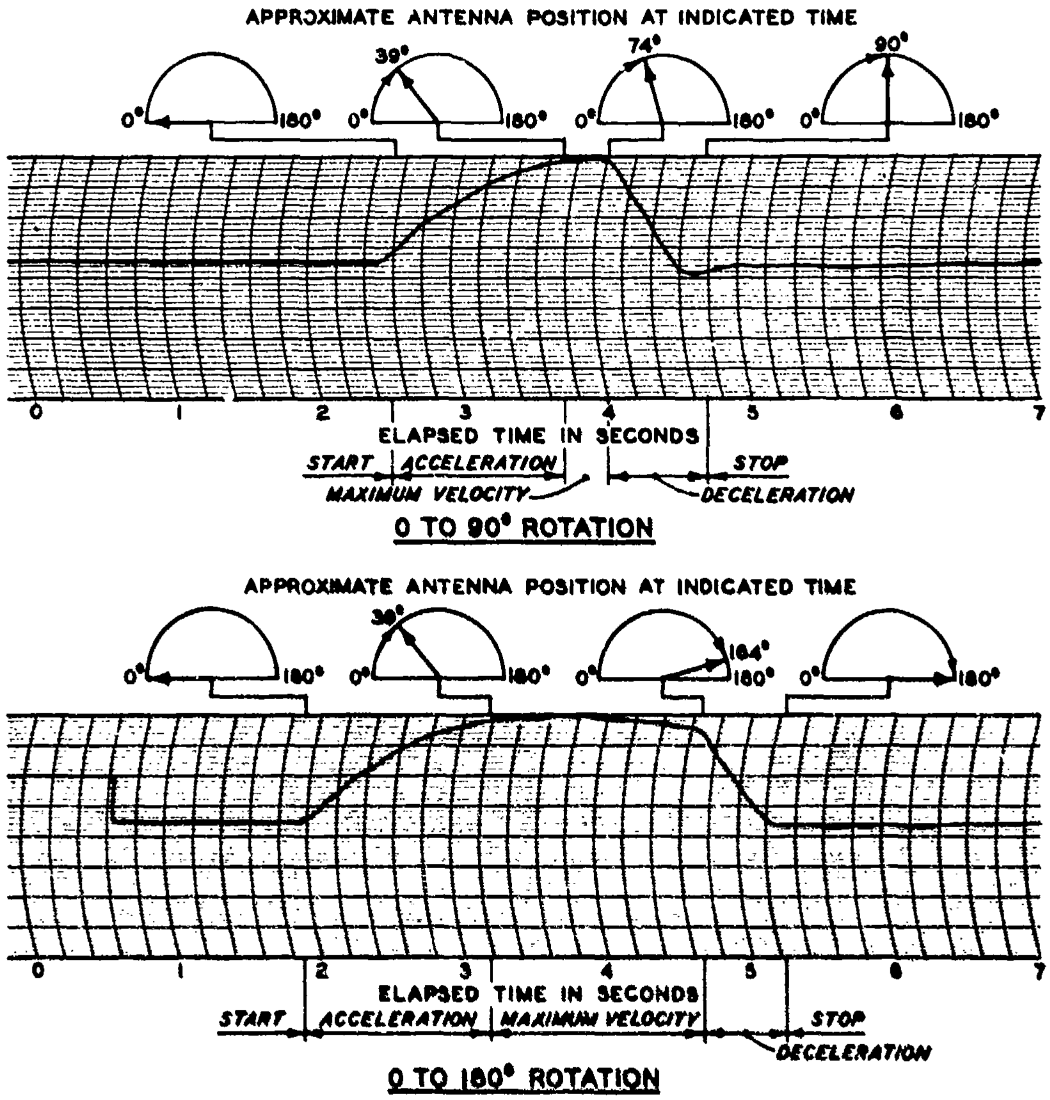
ANTENNA TOWER DETAILS
BAFS
SECTION A-A
ELEVATION
LEGEND
GROUP OF THREE PICKUPS: V_Z, H_X, H_Y
INSTRUMENTED COLUMN
Y-AXIS
X-AXIS
Z-AXIS
-N-
6B12
LOCATION 1
HIGH POINT OF PLATFORM
LOCATION 2
LOCATION 3
LOCATION 4
6-3/4" DIAM (SOLID)
GRADE EL 1543.0

PLATE 3



ANTENNA TOWER DETAILS
KAFB

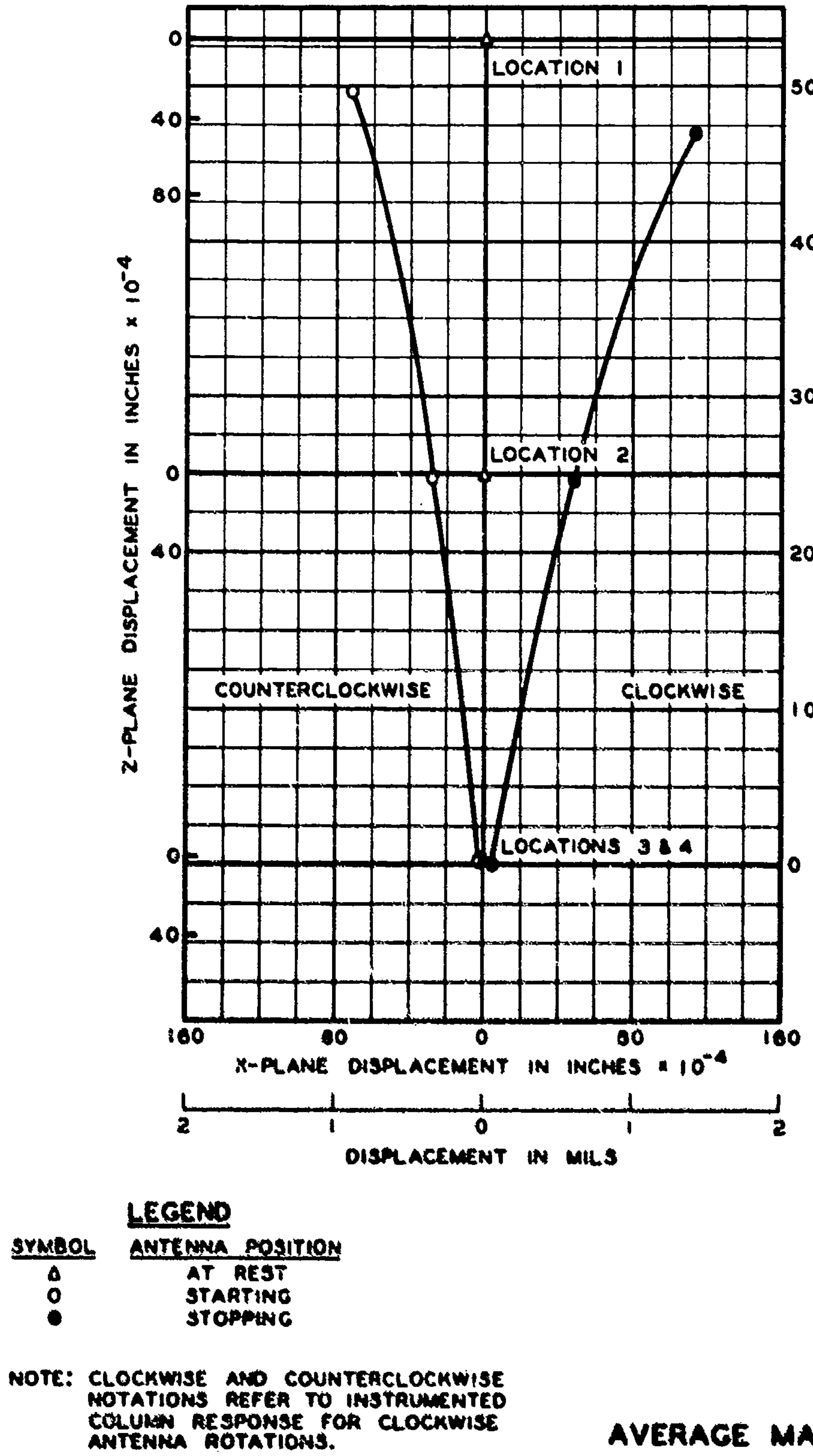
PLATE 4



TYPICAL TACHOMETER RECORDINGS

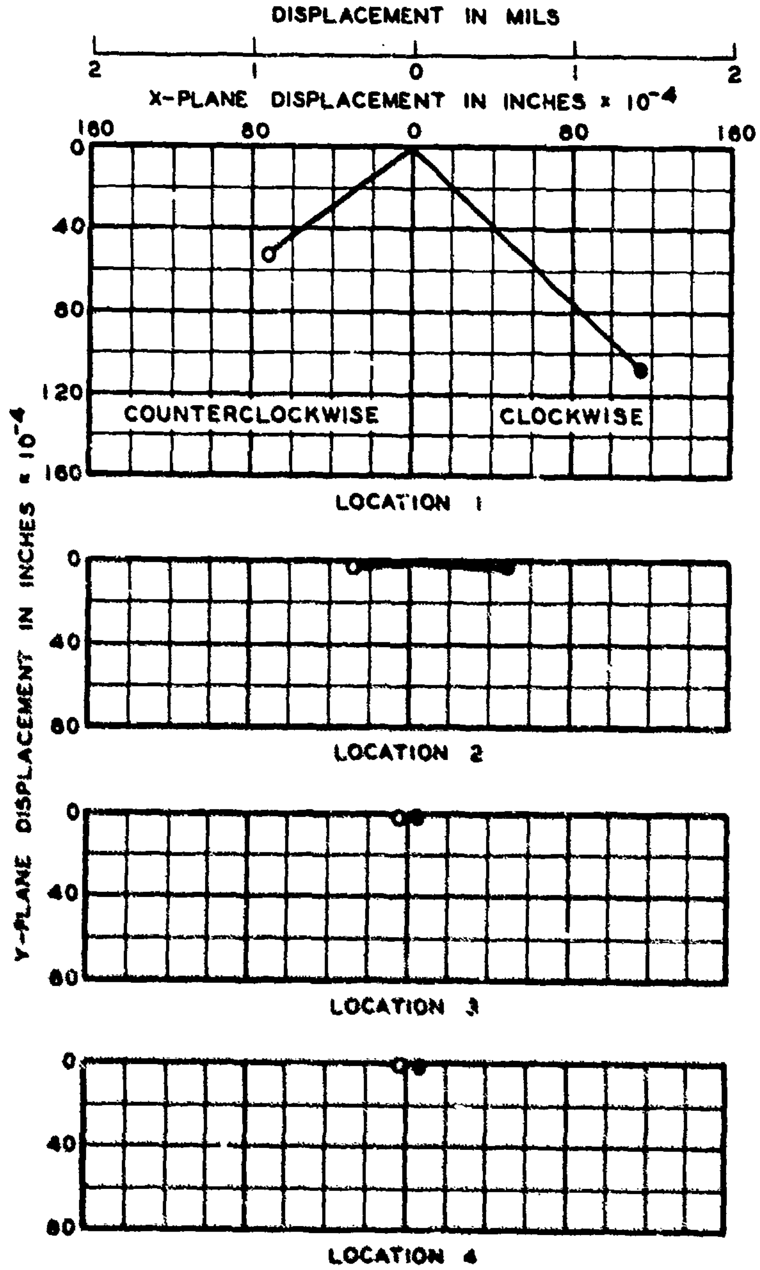
BAFS AND KAFB TOWERS

PLATE 5



AVERAGE MAXIMUM DISPLACEMENTS ALONG X-Z PLANE, BAFS

PLATE 6

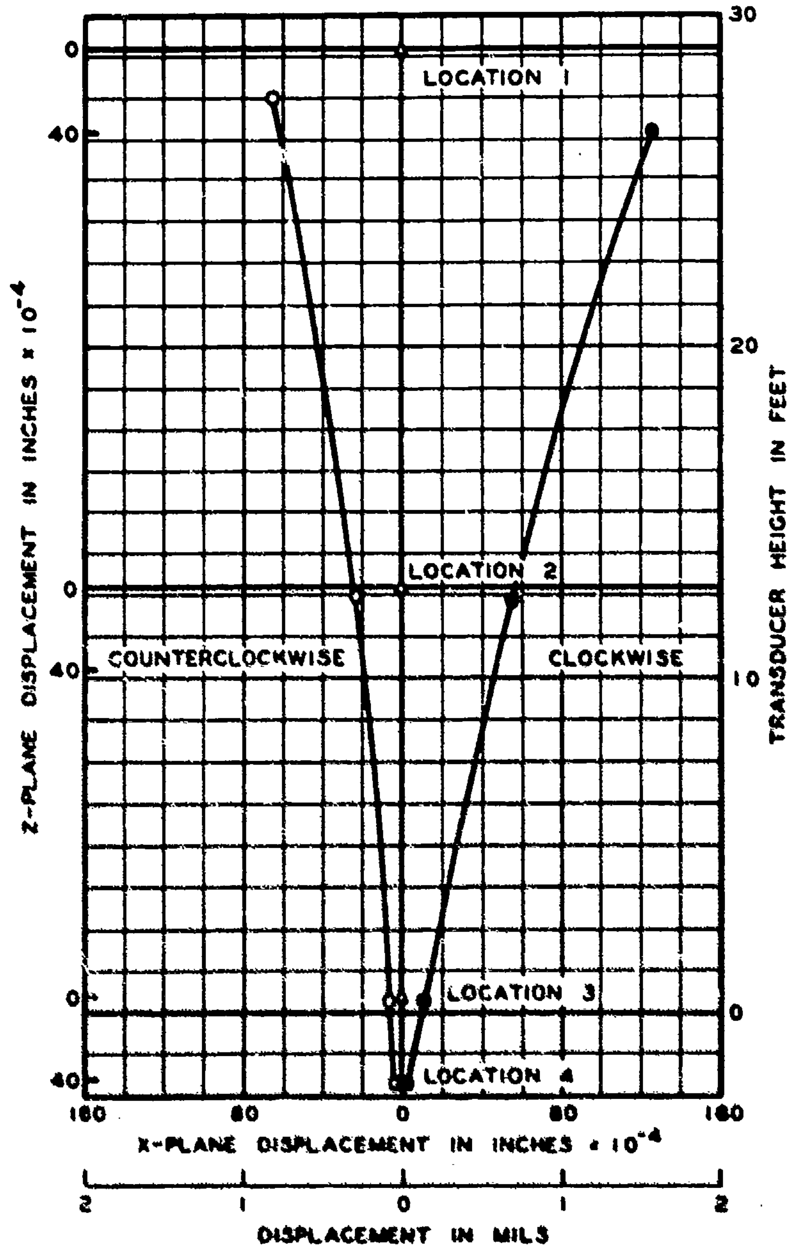


LEGEND

SYMBOL	ANTENNA POSITION
O	STARTING
●	STOPPING

NOTE: CLOCKWISE AND COUNTERCLOCKWISE NOTATIONS REFER TO INSTRUMENTED COLUMN RESPONSE FOR CLOCKWISE ANTENNA ROTATIONS.

AVERAGE MAXIMUM DISPLACEMENTS ALONG X-Y PLANE, BAFS



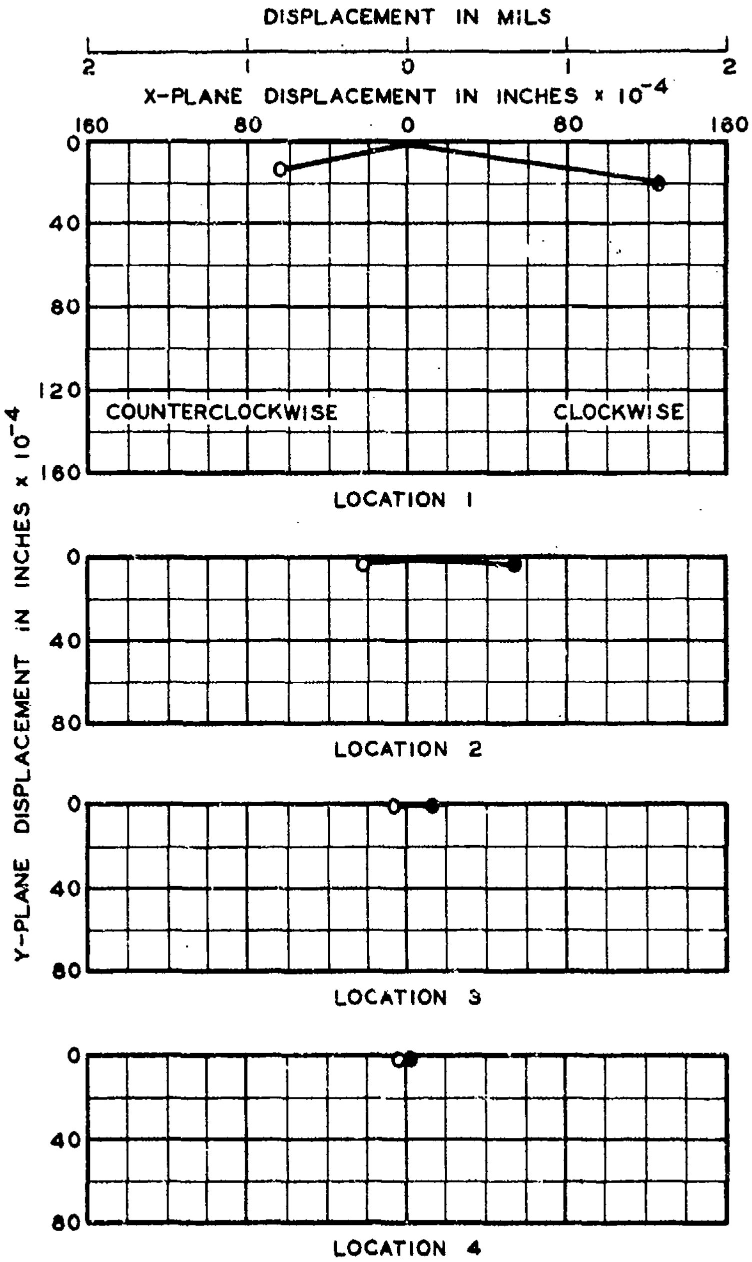
LEGEND

SYMBOL	ANTENNA POSITION
Δ	AT REST
O	STARTING
●	STOPPING

NOTE: CLOCKWISE AND COUNTERCLOCKWISE NOTATIONS REFER TO INSTRUMENTED COLUMN RESPONSE FOR CLOCKWISE ANTENNA ROTATIONS.

AVERAGE MAXIMUM DISPLACEMENTS ALONG X-Z PLANE, KAFB

PLATE 8

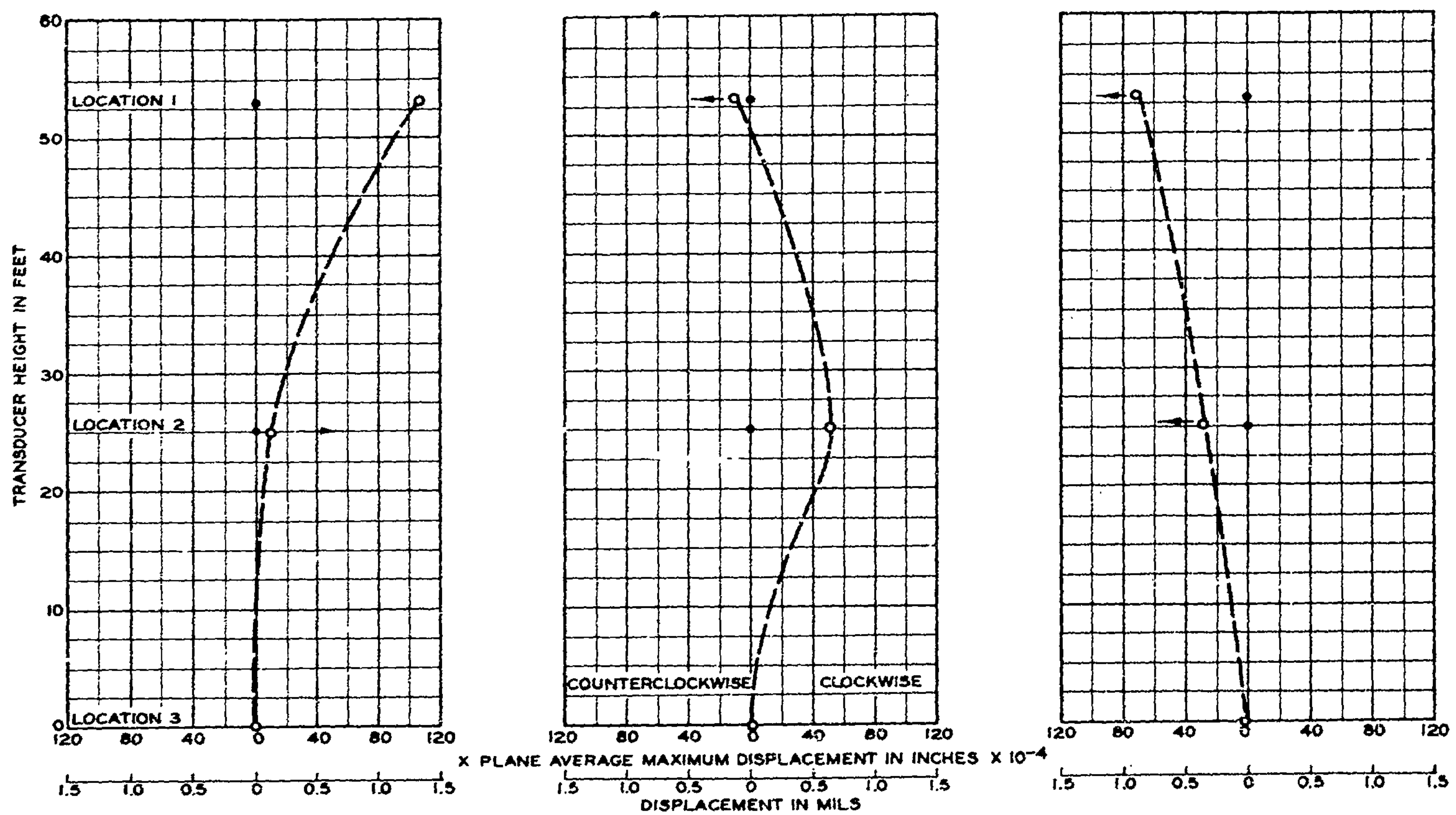


LEGEND

SYMBOL	ANTENNA POSITION
O	STARTING
●	STOPPING

NOTE: CLOCKWISE AND COUNTERCLOCKWISE NOTATIONS REFER TO INSTRUMENTED COLUMN RESPONSE FOR CLOCKWISE ANTENNA ROTATIONS.

AVERAGE MAXIMUM DISPLACEMENTS ALONG X-Y PLANE, KAFB



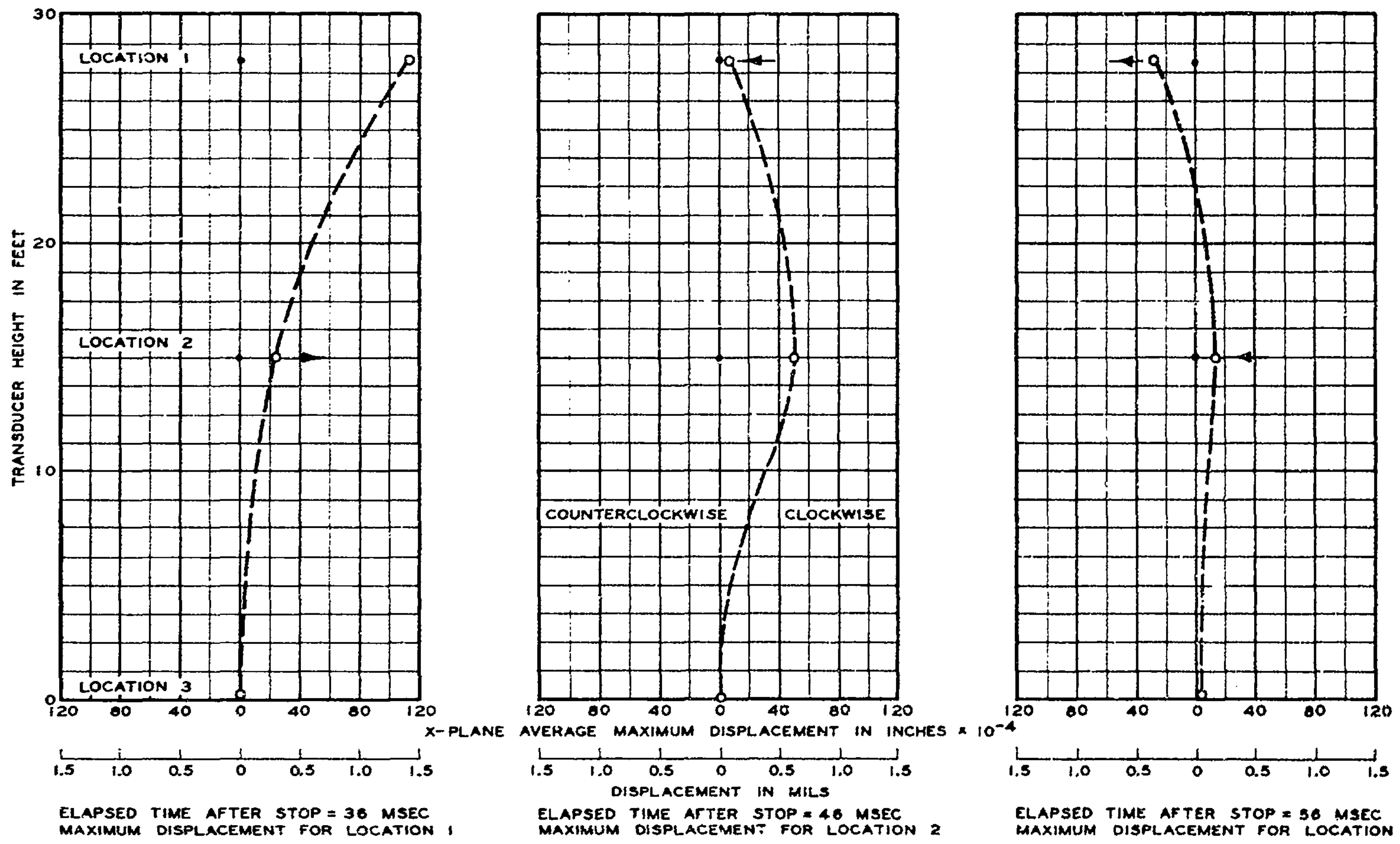
ELAPSED TIME AFTER STOP = 36 MSEC
MAXIMUM DISPLACEMENT FOR LOCATION 1

ELAPSED TIME AFTER STOP = 66 MSEC
MAXIMUM DISPLACEMENT FOR LOCATION 2

ELAPSED TIME AFTER STOP = 96 MSEC
MAXIMUM DISPLACEMENT FOR LOCATION 3

NOTE: CLOCKWISE AND COUNTERCLOCKWISE NOTATIONS REFER TO INSTUMENTED COLUMN RESPONSE FOR CLOCKWISE ANTENNA ROTATIONS.

TIME-PHASE RELATION, BAFS
STOPPING MOVEMENT ONLY



NOTE: CLOCKWISE AND COUNTERCLOCKWISE NOTATIONS REFER TO INSTRUMENTED COLUMN RESPONSE FOR CLOCKWISE ANTENNA ROTATIONS.

TIME-PHASE RELATION, KAFB
STOPPING MOVEMENT ONLY